

12

**B  
R  
L**

**AD-A148 896**

**AD**

**TECHNICAL REPORT BRL-TR-2610**

**ACCELERATION MEASUREMENTS  
IN HIGH G ENVIRONMENTS**

**James O. Pilcher II**

**November 1984**

**DTIC  
ELECTE  
JAN 7 1985  
B**

**DTIC FILE COPY**

**APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.**

**US ARMY BALLISTIC RESEARCH LABORATORY  
ABERDEEN PROVING GROUND, MARYLAND**

**84 12 11 068**

**BLANK PAGES  
IN THIS  
DOCUMENT  
WERE NOT  
FILMED**

Destroy this report when it is no longer needed.  
Do not return it to the originator.

Additional copies of this report may be obtained  
from the National Technical Information Service,  
U. S. Department of Commerce, Springfield, Virginia  
22161.

The findings in this report are not to be construed as an official  
Department of the Army position, unless so designated by other  
authorized documents.

The use of trade names or manufacturers' names in this report  
does not constitute indorsement of any commercial product.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER <b>TECHNICAL REPORT BRL-TR-2610</b>	2. GOVT ACCESSION NO. <b>AD-A148896</b>	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle)  <b>ACCELERATION MEASUREMENTS IN HIGH G ENVIRONMENTS</b>		5. TYPE OF REPORT & PERIOD COVERED  <b>Final Report</b>
7. AUTHOR(s)  <b>JAMES O. PILCHER II</b>		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS <b>US Army Ballistic Research Laboratory ATTN: AMXBR- IBD Aberdeen Proving Ground, MD 21005-5066</b>		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS <b>US Army Ballistic Research Laboratory ATTN: AMXBR-OD-ST Aberdeen Proving Ground, MD 21005-5066</b>		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS  <b>1L162618AH80</b>
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE <b>November 1984</b>
		13. NUMBER OF PAGES <b>26</b>
		15. SECURITY CLASS. (of this report)  <b>UNCLASSIFIED</b>
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  <b>Approved for public release; distribution is unlimited.</b>		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES  <b>This report was presented and published as a paper at the 1982 American Control Conference, Alexandria, VA, June 1982. (Invited paper) (New data was used in the figures)</b>		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) <b>Acceleration Measurements Interference Filtering Arrays Calibration</b>		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <b>Jmk</b> <b>This report discusses the difficulties encountered in acceleration measurements performed on gun and projectile systems and the techniques used to circumvent these difficulties. Particular points of discussion are the use of mechanical, digital and electronic filtering techniques and their limitations.</b>		

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# TABLE OF CONTENTS

	Page
LIST OF ILLUSTRATIONS.....	5
I. INTRODUCTION.....	7
A. <u>The Measurement Problem</u> .....	7
B. <u>Approach to the Problem</u> .....	7
II. THE HIGH G ACCELERATION ENVIRONMENT.....	8
III. MECHANICAL FILTERING.....	11
IV. SPATIAL ARRAY TECHNIQUES.....	14
V. ELECTRONIC AND NUMERICAL FILTERING.....	17
VI. REQUIREMENT FOR CALIBRATION AND SENSOR CAPACITY.....	18
A. <u>Calibration Requirements</u> .....	18
B. <u>General Response Requirements</u> .....	19
C. <u>User Responsibility</u> .....	20
VII. SUMMARY.....	20
REFERENCES.....	21
DISTRIBUTION LIST.....	23

DTIC  
ELECTE  
S JAN 7 1985 D  
B

Accession For	
DTIC	<input checked="" type="checkbox"/>
DTIC	<input type="checkbox"/>
DTIC	<input type="checkbox"/>
JAN 7 1985	
By	
Distribution/	
Avail. Utility Codes	
Avail. and/or	
Dist. Special	
A-1	



## LIST OF ILLUSTRATIONS

Figures		Page
1	Typical Gun Muzzle Acceleration Signal.....	8
2	Fourier Spectrum of the Signal in Figure 1.....	9
3	Data in Figure 1 Low-Pass Filtered at 8 kHz.....	10
4	Position Vector.....	11
5	Typical Mechanical Filter.....	13
6	Comparison of Filter Characteristics.....	13
7	Shock Test Verification of Filter Operation.....	14
8	Collinear 3-Pair Accelerometer Array.....	17
9	Orthogonal Sensitivity Properties.....	19

## I. INTRODUCTION

Over the past ten years, the Ballistic Research Laboratory (BRL) has been striving to develop accurate means of predicting the dynamic behavior of gun systems. Particularly, the major concerns are those effects that dominate the launch conditions of the projectile and its subsequent terminal performance. The basic objective of the acceleration measurement techniques discussed is to determine the dynamic structural response of guns and projectiles in order to verify theoretical predictions. These measurements are made in real gun systems which impose severe environmental conditions that contain interference phenomena which often dominate the outputs of the measurement system, rendering the measurements useless for their purpose. In spite of the difficulties encountered, viable acceleration measurements can be obtained by addressing the nature of the environmental interference and the structural response.

### A. The Measurement Problem

The measurement problem is one of being able to discriminate the significant motion vector from a complex combination of vector components which are generated by various dynamic phenomena including the ones of interest. Unlike well-controlled laboratory experiments designed to separate various physical phenomena, ballistic system measurements are subject to interference from local accelerations generated by stress waves, blast waves, dilatational vibrations, traveling loads, impulses, and impacts at mechanical interfaces. Often the resulting interfering accelerations have a greater magnitude than the measurand.

### B. Approach to the Problem

To gain a meaningful acceleration measurement, one must exploit the characteristics of the physical phenomena encountered during the measurement. In this discussion, the global structural motion is paramount. Therefore, emphasis is placed on the low frequency responses of ballistic systems, that is, those below 10 kHz. However, higher frequency responses cannot be ignored or disregarded. The high frequency responses of ballistic systems (generally from 8 kHz to 60 kHz) must be considered for their effect on the transducer system and their pollution of the desired data. The measurand must be considered as a six-degrees-of-freedom phenomenon, and the sensor must be considered to have a multidegree-of-freedom response, depending on the design of the specific sensor used.

Interferences in the measurement from environmental conditions can be eliminated or minimized by numerical, electronic and mechanical filtering techniques. However, these filters must be designed for each specific situation.

The separation of the desired vector components of motion can be achieved through the deliberate design of sensor arrays and their associated data processing algorithms. The theoretical predictions must be cast in the same vector component combinations as the measurement. This technique is enhanced through the selection of matched pairs of sensors.

The following discussion reviews the characteristics of the environment, measurand and sensors, and the applications of filters, sensor arrays and calibrations as well as their requirements and limitations.

## II. THE HIGH G ACCELERATION ENVIRONMENT

Before proceeding, a definition is in order. A "G" is defined as one standard gravitational acceleration unit,  $32.2 \text{ ft/sec}^2$  or  $9.8 \text{ m/sec}^2$ .

For modern ballistic systems, accelerations can be expected with measurands ranging from 5 Hz to 10 kHz in the frequency domain and from 0 kG to 50 kG in the magnitude domain. Superimposed on these measurands are interfering accelerations ranging from 10 kHz to 60 kHz in the frequency domain and 2 kG to 10 kG in the magnitude domain. The desired measurands can be reasonably estimated for instrumentation purposes. However, the interfering acceleration environment cannot be readily estimated. Sources of the interfering accelerations are strain waves, impacts and impulses which cause the sensor to resonate, overload, and/or respond nonlinearly. Even if a sensor is not permanently damaged, which is often the case, the output has been modified by sensor-generated baseline shifts and frequency components caused by the nonlinear response of the sensor. This condition often renders the data from the measurement unintelligible. Figure 1 shows the output of a piezoelectric accelerometer which is dominated by stress wave interference.

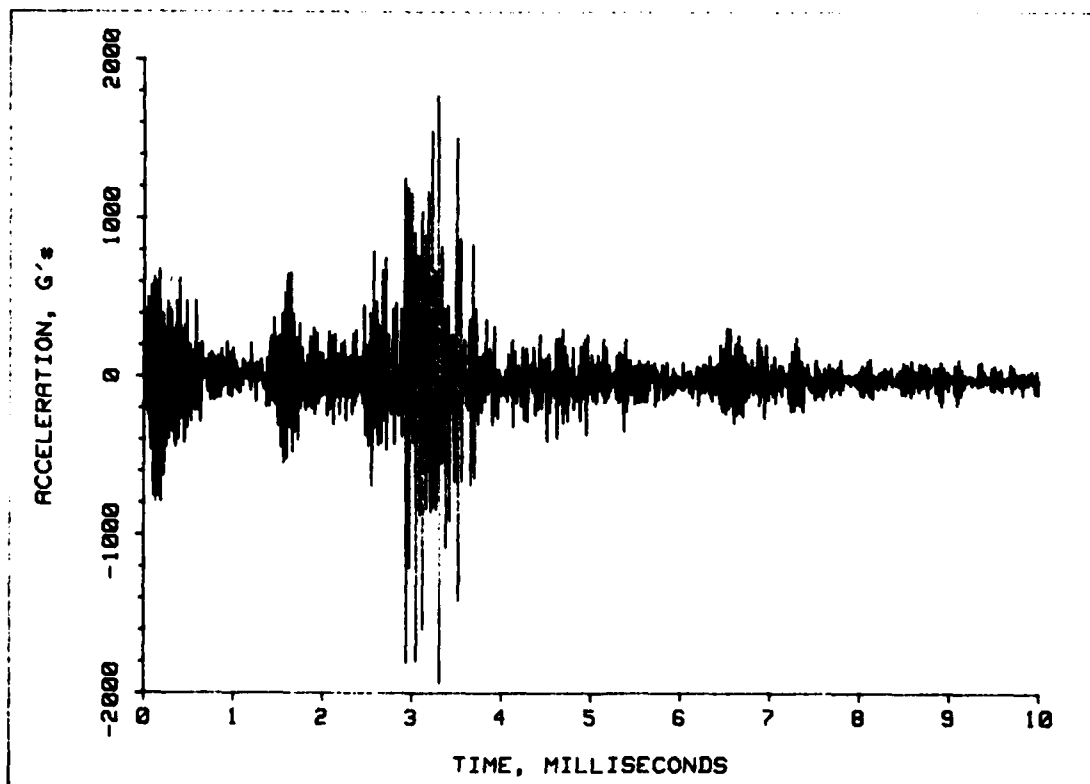


Figure 1. Typical Gun Muzzle Acceleration Signal



In this case, the accelerometer is mounted directly to the muzzle of a 75-mm gun. The bandwidth of the acquisition system is 100 kHz. The linear response of the accelerometer is 6 kHz.

The expected maximum acceleration of the structure is 350 G with significant modes up to 1.5 kHz. This accelerometer was subjected to accelerations in excess of 2000 G peak but did not suffer permanent damage, a fact verified by subsequent recalibration. In this case, baseline shifts occurred due to excitation over the nonlinear range of the accelerometer. Figure 2 shows the normalized amplitude spectrum of the signal in Figure 1.

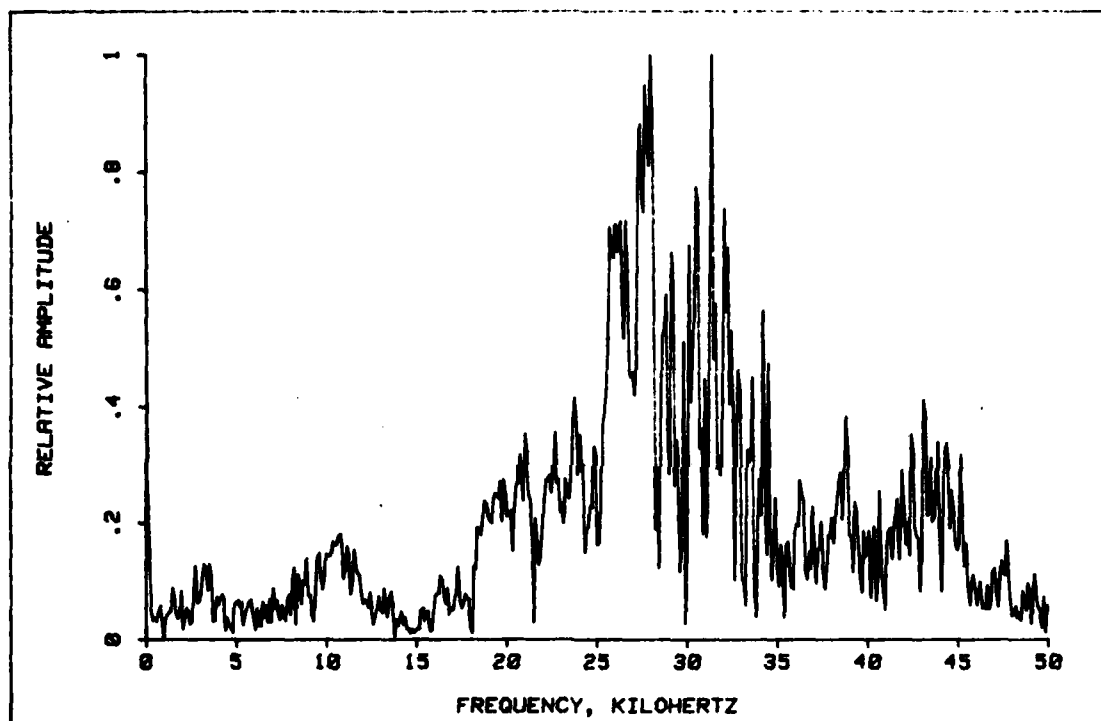


Figure 2. Fourier Spectrum of the Signal in Figure 1

This spectrum shows a reasonable separation of the frequency content of the measurand from the interference. However, merely filtering the output signal numerically or electronically will not remove baseline shifts or spurious frequencies in the range of the measurand frequencies. Figure 3 shows the appearance of the measurand after low pass numerical filtering at 6 kHz. Although the filter removes the high frequency components of the data which masked the measurand, it does not remove the baseline shift and the self-generated low frequencies caused by the nonlinear response of the sensor to the interference.

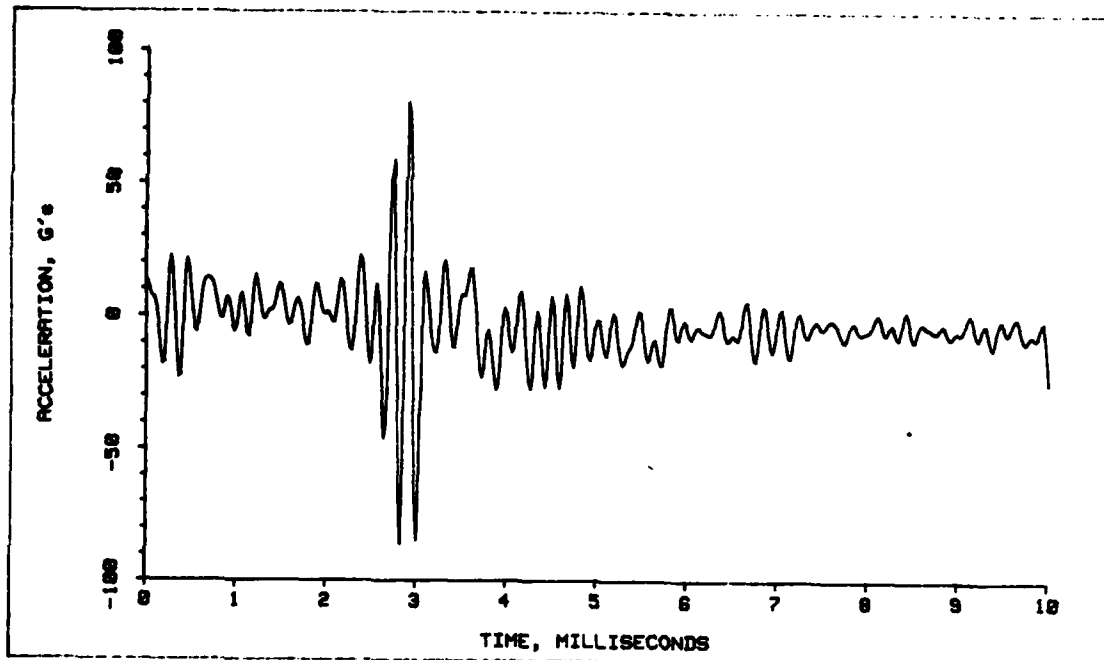


Figure 3. Data in Figure 1 Low-Pass Filtered at 8 kHz

Mathematically, the excitation at the input to the accelerometer can be expressed by the second time derivative of the sensor's position vector,

$\mathbf{P} = \mathbf{R} + \mathbf{r}$ . The unit vectors of the earth coordinates are  $\mathbf{U}_x^e$ ,  $\mathbf{U}_y^e$  and  $\mathbf{U}_z^e$ . The unit vectors of the sensor coordinates are  $\mathbf{U}_x^s$ ,  $\mathbf{U}_y^s$ , and  $\mathbf{U}_z^s$  with their origin at the center of gravity of the local structural element. The position vector is diagramed in Figure 4.

The vector  $\mathbf{R}$  is the relative position vector of the origin of the local coordinate system with respect to the earth's coordinate system. The local coordinate system translates and rotates with respect to the earth's coordinate system as a function of time. The vector  $\mathbf{r}$  is the position of the point of observation with respect to the origin of the local coordinate system. Since the local coordinate system undergoes rotation, the first time derivative of the unit vector  $\mathbf{U}$  is defined as the angular velocity vector,  $\boldsymbol{\omega}$ .<sup>1</sup> It can be shown that the acceleration vector,  $\mathbf{A}$ , at the point of observation is<sup>2</sup>

<sup>1</sup> S.W. McCuskey, *Introduction to Advanced Dynamics*, Addison-Wesley Publishing Company, Reading, MA, pp 28-33, 1958.

<sup>2</sup> J.O. Pilcher II, "Theoretical Consideration in Measuring Six-Degree-of-Freedom Motion of Gun Tubes by Accelerometers," ARBRL-TR-02474, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1983. (AD# A125474)

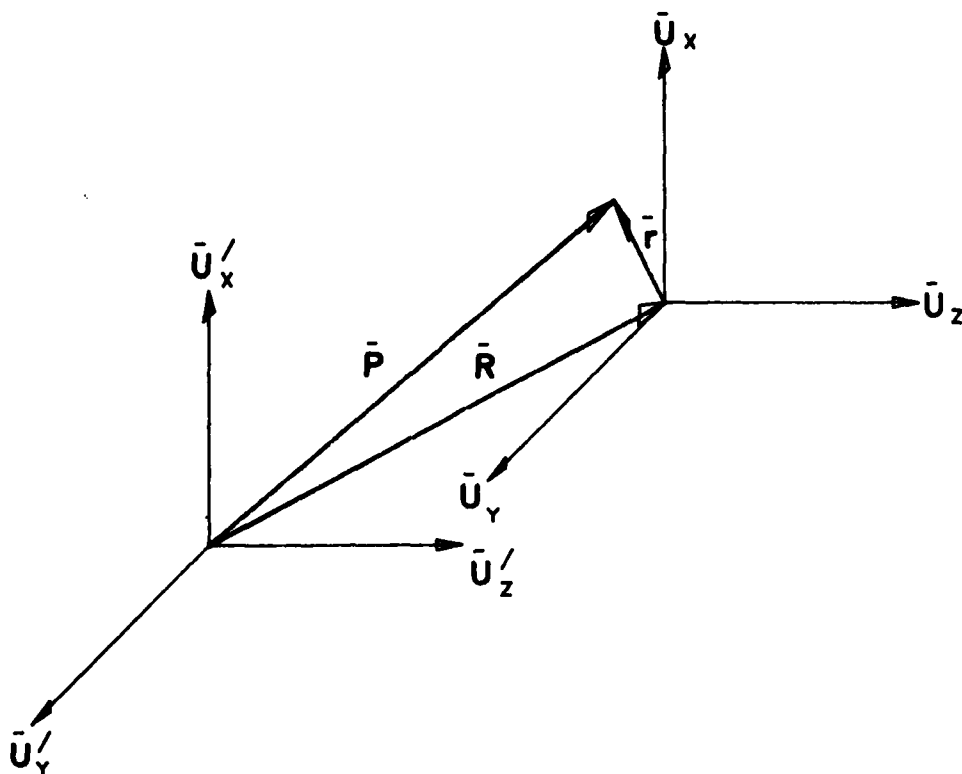


Figure 4. Position Vector

$$\mathbf{A} = \frac{d^2 \mathbf{P}}{dt^2} = [\ddot{\mathbf{R}} + 2(\boldsymbol{\omega} \times \dot{\mathbf{R}}) + (\boldsymbol{\omega} \cdot (\mathbf{R} + \mathbf{r}))\boldsymbol{\omega} - (\boldsymbol{\omega} \cdot \boldsymbol{\omega})(\mathbf{R} + \mathbf{r}) + \dot{\boldsymbol{\omega}} \times (\mathbf{R} + \mathbf{r})] + [\ddot{\mathbf{r}} + 2(\boldsymbol{\omega} \times \dot{\mathbf{r}})]. \quad (1)$$

The terms in the first bracket in Eq. (1) represent the accelerations due to rigid-body motion of the element. The vectors  $\dot{\mathbf{R}}$  and  $\dot{\boldsymbol{\omega}}$  are usually the desired measurands but are not generally separable from the remaining terms. The terms in the second bracket represent the accelerations due to local deformations. The frequency domain of these accelerations corresponds to the band of higher frequencies shown in Figure 2. In the case of gun tube measurements, the magnitudes of the local deformation accelerations are one to two orders of magnitude greater than the magnitudes of the rigid-body accelerations.

### III. MECHANICAL FILTERING

In spite of the difficulties encountered, mechanical filtering offers the most viable approach to eliminating the high frequency accelerations from the measurement. However, this technique cannot be blindly applied. A preliminary measurement must be made without filtering to determine the filter

requirements. Once these requirements have been established, the design of the filter can proceed. The operation of the filter must be verified through appropriate testing done over the ranges of magnitudes before it is used for measurement purposes. This is particularly necessary since mechanical filter design is based on approximate theory and is still an art at best.

A filter design used at the BRL is based on the viscoelastic and attenuation properties of felt, which is the medium for the spring and damping elements of the filter. It is designed as a parallel transfer impedance filter.

$$\frac{1}{Z_C} = \frac{1}{Z_R} + \frac{1}{Z_{WC}} + \frac{1}{Z_{WS}} + \frac{1}{Z_{WT}}, \quad (2)$$

where  $Z_C$  = the characteristic impedance, and of the filter;

$Z_R$  = the rigid body impedance;

$Z_{WC}$ ,  $Z_{WS}$ ,  $Z_{WT}$  = the wave effect impedance due to compression, shear and torsion, respectively.

$Z_R$  is determined by the classical theory of vibrations and  $Z_{WC}$ ,  $Z_{WS}$ ,  $Z_{WT}$  are determined by computing the wave impedances.

$$Z_C = \frac{Z_R Z_{WC} Z_{WS} Z_{WT}}{Z_{WC} Z_{WS} Z_{WT} + Z_R (Z_{WC} Z_{WT} + Z_{WS} Z_{WT} + Z_{WS} Z_{WC})}. \quad (3)$$

The wave impedances can be estimated for simple geometries by the models tabulated in Table 30.3 on pages 30-53 of reference 3. Figure 5 shows one of the physical embodiments of a filter. Figure 6 shows the characteristics of the filter in Figure 5 compared with the characteristics of a similar filter using an elastomeric material instead of felt. The fibrous structure of the felt contains numerous scattering surfaces which enhance the attenuation of high frequencies. In this case, the cutoff frequency is designed to be 3 kHz. Figure 7 shows a comparison of the mechanically filtered and mechanically unfiltered shock pulse measure during operational tests of the filter.<sup>4</sup>

<sup>3</sup> C.M. Harris and C.E. Crede, *Shock and Vibration Handbook Vol. 2*, McGraw-Hill Book Company Inc., New York, Chapter 30, p. 53, 1961.

<sup>4</sup> J.O. Pilcher, "Application of Mechanical Filters to Ballistic Measurements," *Ballistic Research Laboratory, Aberdeen Proving Ground, MD, forthcoming.*

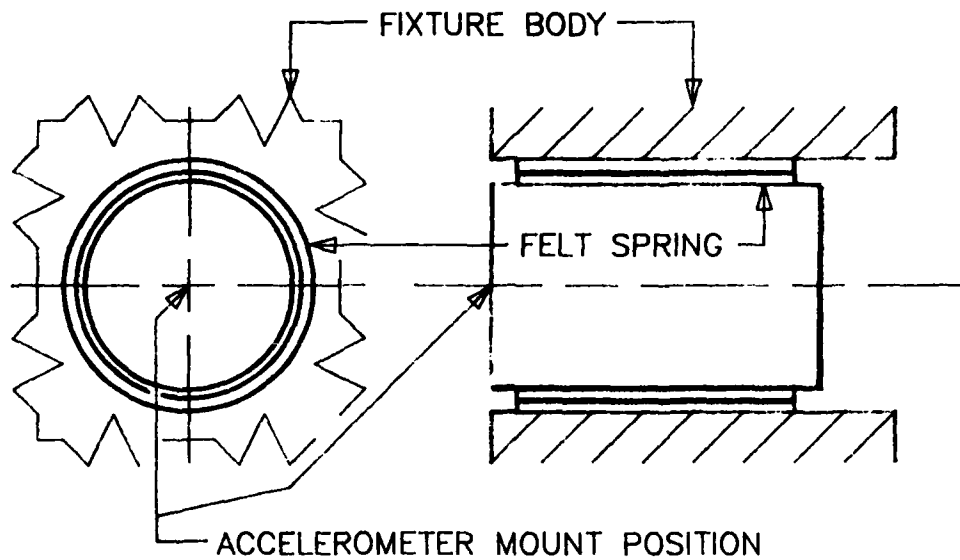


Figure 5. Typical Mechanical Filter

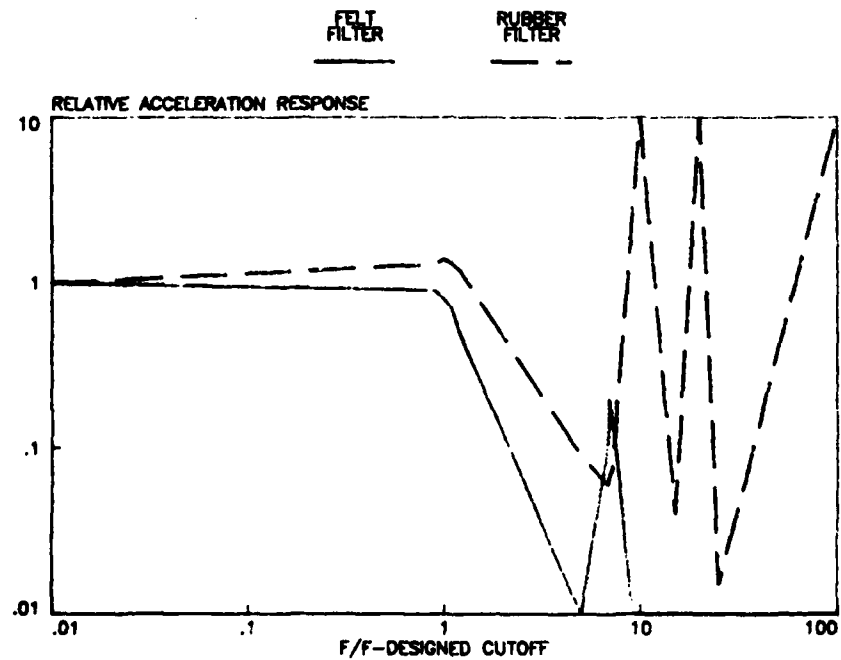


Figure 6. Comparison of Filter Characteristics

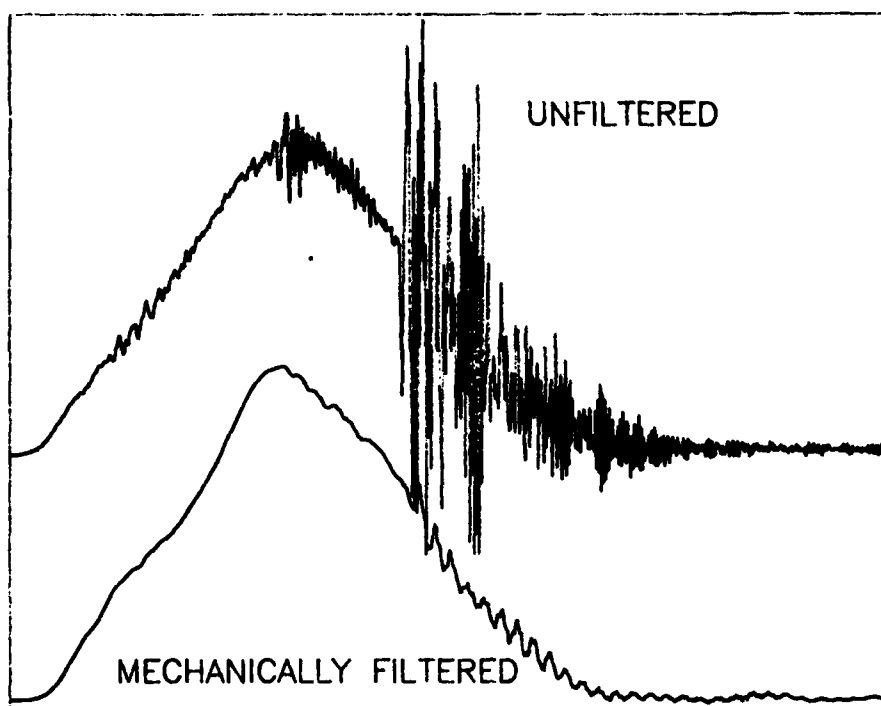


Figure 7. Shock Test Verification of Filter Operation

#### IV. SPATIAL ARRAY TECHNIQUES

Once the high frequency interference has been eliminated or reduced to an insignificant level, the measuring system must be designed to resolve various vector components. Certain combinations of sensors must be used depending on the primary purpose of the data to be collected. This requires an examination of the accelerometer response to the imposed motion. The accelerometer response can be expressed as a vector,  $G$ .

$$G = aU_x + bU_y + cU_z \quad (4)$$

where  $a, b$ , and  $c$  are the response coefficients along the local unit vectors.

The coefficients of Eq. (4) are the principal gage factor and the two orthogonal cross-axis gage factors. The equation can be expressed in terms of the principal gage factor,  $P$ , and the ratios of the cross-axis gage factors to the principal gage factor,  $k_1$  and  $k_2$  (usually expressed in percent in the literature). For a specific gage arrangement, where the principal axis is along  $U_x$ ,

$$G = P (U_x + k_1U_y + k_2U_z). \quad (5)$$

The output,  $O$ , is the dot product of the gage response vector,  $G$ , with the local acceleration vector,  $A$  (given in Eq. (1)).

$$\begin{aligned}
 O = G \cdot A = P \{ & [\ddot{R}_x + \omega_x \omega_y (R_y + r_y) + \omega_x \omega_z (R_z + r_z) \\
 & - (R_x + r_x)(\omega_y^2 + \omega_z^2) + 2\omega_y \dot{R}_z - 2\omega_z \dot{R}_y \\
 & + \dot{\omega}_y (R_z + r_z) - \dot{\omega}_z (R_y + r_y)] \\
 & + k_1 [\ddot{R}_y + \omega_y \omega_z (R_z + r_z) + \omega_y \omega_x (R_x + r_x) \\
 & - (R_y + r_y)(\omega_z^2 + \omega_x^2) + 2\omega_z \dot{R}_x - 2\omega_x \dot{R}_z \\
 & + \dot{\omega}_z (R_x + r_x) - \dot{\omega}_x (R_z + r_z)] \\
 & + k_2 [\ddot{R}_z + \omega_z \omega_x (R_x + r_x) + \omega_z \omega_y (R_y + r_y) \\
 & - (R_z + r_z)(\omega_x^2 + \omega_y^2) + 2\omega_x \dot{R}_y - 2\omega_y \dot{R}_x \\
 & + \dot{\omega}_x (R_y + r_y) - \dot{\omega}_y (R_x + r_x)] \} . \quad (6)
 \end{aligned}$$

The complicated equation above can be simplified by using matched pairs of accelerometers mounted in symmetrical arrays about the origin of the local coordinate system. Matched accelerometers have the same cross-axis sensitivity. Figure 8 shows the schematic layout for a six accelerometer col-linear array for measuring the local motion of a gun tube. All six accelerometers lie on the same axis. Accelerometers 1 and 3 have their principal axes along  $U_x$ ; accelerometers 5 and 7 have their principal axes along  $U_y$ ; accelerometers 9 and 11 have their principal axes along  $U_z$ . Vector components for this array can be discriminated using the following algorithms.

$$M_x = \left(\frac{G_1 - G_3}{2}\right) - k_1 \left(\frac{G_5 - G_7}{2}\right) - k_2 \left(\frac{G_9 - G_{11}}{2}\right)$$

$$= \ddot{R}_x + \omega_x \omega_y R_y + \omega_x \omega_z R_z - R_x (\omega_y^2 + \omega_z^2) + 2\omega_y R_z - 2\omega_z R_y + \dot{\omega}_y R_z - \dot{\omega}_z R_y ;$$

$$M_y = \left(\frac{G_5 - G_7}{2}\right) - k_1 \left(\frac{G_9 - G_{11}}{2}\right) - k_2 \left(\frac{G_1 - G_3}{2}\right)$$

$$= \ddot{R}_y + \omega_y \omega_z R_z + \omega_y \omega_x R_x - R_y (\omega_x^2 + \omega_z^2) + 2\omega_z R_x - 2\omega_x R_z + \dot{\omega}_z R_x - \dot{\omega}_x R_z ;$$

$$M_z = \left(\frac{G_9 - G_{11}}{2}\right) - k_1 \left(\frac{G_1 - G_3}{2}\right) - k_2 \left(\frac{G_5 - G_7}{2}\right)$$

$$= \ddot{R}_z + \omega_z \omega_x R_x + \omega_z \omega_y R_y - R_z (\omega_x^2 + \omega_y^2) + 2\omega_x R_y - \omega_y R_x + \dot{\omega}_x R_y - \dot{\omega}_y R_x ;$$

$$(\omega_y^2 + \omega_z^2) = \frac{1}{r_1} \left[ -\left(\frac{G_1 + G_3}{2}\right) + k_1 \left(\frac{G_5 + G_7}{2}\right) + k_2 \left(\frac{G_9 + G_{11}}{2}\right) \right] ;$$

$$(\omega_y \omega_x + \dot{\omega}_z) = \frac{1}{r_5} \left[ \left(\frac{G_5 + G_7}{2}\right) - k_1 \left(\frac{G_9 + G_{11}}{2}\right) - k_2 \left(\frac{G_1 + G_3}{2}\right) \right] ; \text{ and}$$

$$(\omega_z \omega_x - \dot{\omega}_y) = \frac{1}{r_9} \left[ \left(\frac{G_9 + G_{11}}{2}\right) - k_1 \left(\frac{G_1 + G_3}{2}\right) - k_2 \left(\frac{G_5 + G_7}{2}\right) \right] , \quad (7)$$

where  $G_i = \frac{O_i}{P_i} .$

Equations (7) are derived in Reference 2.

These equations demonstrate the complexity of the content of the acceleration measurements. Particularly, they show that single components such as  $R_x$  are not separable from the data. This is a situation that must be addressed when the purpose of the measurement is to verify model



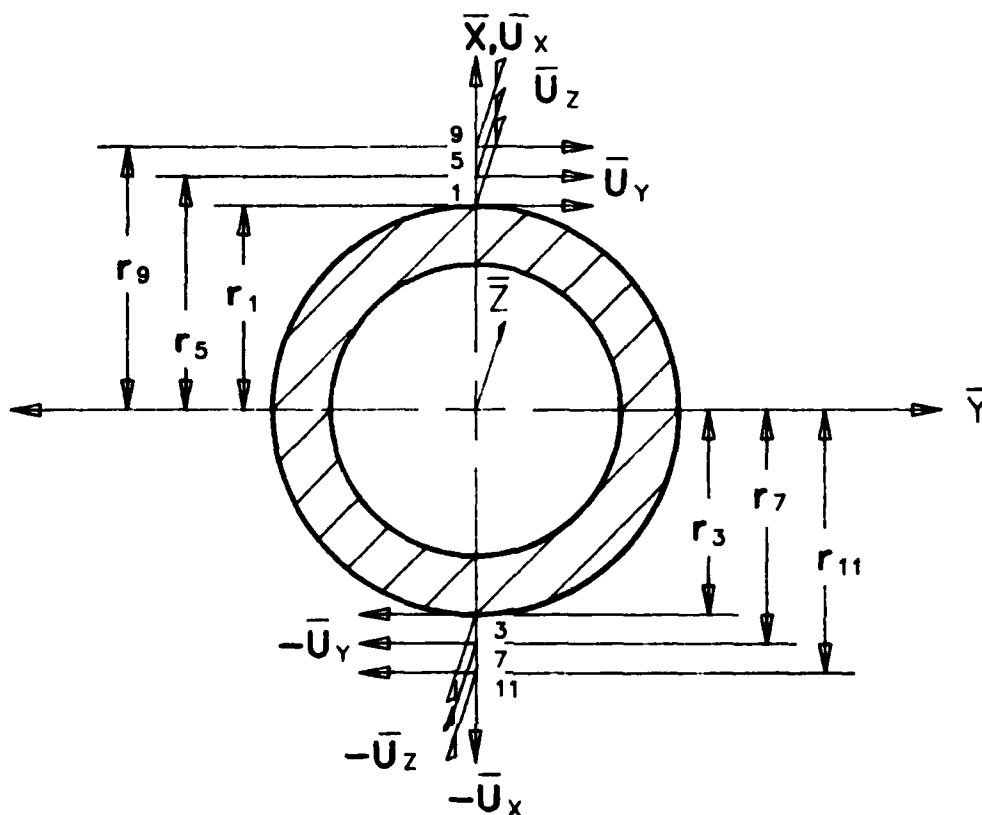


Figure 8. Collinear 3-Pair Accelerometer Array

predictions. Another important consideration is the establishment of the measurement system bandwidth. When vibratory modes are estimated, one must consider that the terms such as  $\omega_x \omega_y R$  will create frequencies which are the sum of the frequencies in the represented vectorial components. As a rule of thumb, one can expect frequencies up to the third harmonic of the highest mode excited. In addition, the spectrum will be filled with the intermediate frequencies of the vector products.

#### V. ELECTRONIC AND NUMERICAL FILTERING

It is common practice to provide electronic filtering between the sensor and the data acquisition system to create improved signal-to-noise ratio, and minimize FM/FM recording distortion. Filtering is also provided to prevent aliasing during digitizing for numerical analyses. These filtering applications should be carried out using constant time delay or constant phase

filters.<sup>5,6</sup> In dynamic measurements, phase shifts become more significant than amplitude error and must be kept to a minimum. Although these types of filtering are often necessary, they present a dilemma to the experimenter in that they often hide difficulties caused by the sensor itself. If the whole sensor/acquisition system has insufficient bandwidth, one will see baseline shifts and sensor-created frequencies due to nonlinearity and overranging, but not the high frequencies causing these problems. In addition, the output signal will be modified to the point that it cannot be reliably analyzed by Fourier transform techniques. It has been our experience that this condition has been the most common source of difficulty in diagnosing sensor problems in ballistic measurements. What is generally required, but often most difficult to obtain, is an instrumentation checkout test of the experiment with wide system bandwidths that allow complete observation of the event to determine the adequacy of the instrumentation's measuring range functioning.

## VI. REQUIREMENT FOR CALIBRATION AND SENSOR CAPACITY

In order to utilize the powerful mathematical techniques available for analyzing accelerometer measurements, more extensive calibration information is required than is generally provided. In addition, more stringent requirements should be placed on the accelerometer for both survival and measurement capabilities.

### A. Calibration Requirements

Calibration requirements generally extend the information available in both the space and frequency domain.

1. A complete vector description of accelerometer sensitivity requires a calibration of the sensor sensitivity in two mutually orthogonal planes as shown in Figure 9.

2. A complete description of the nonlinear sensor sensitivity requires sufficient data points over the whole range of measurement to adequately determine the coefficients for at least a third order description. The process is required for both the principal axis of sensitivity and the cross axes of sensitivity.

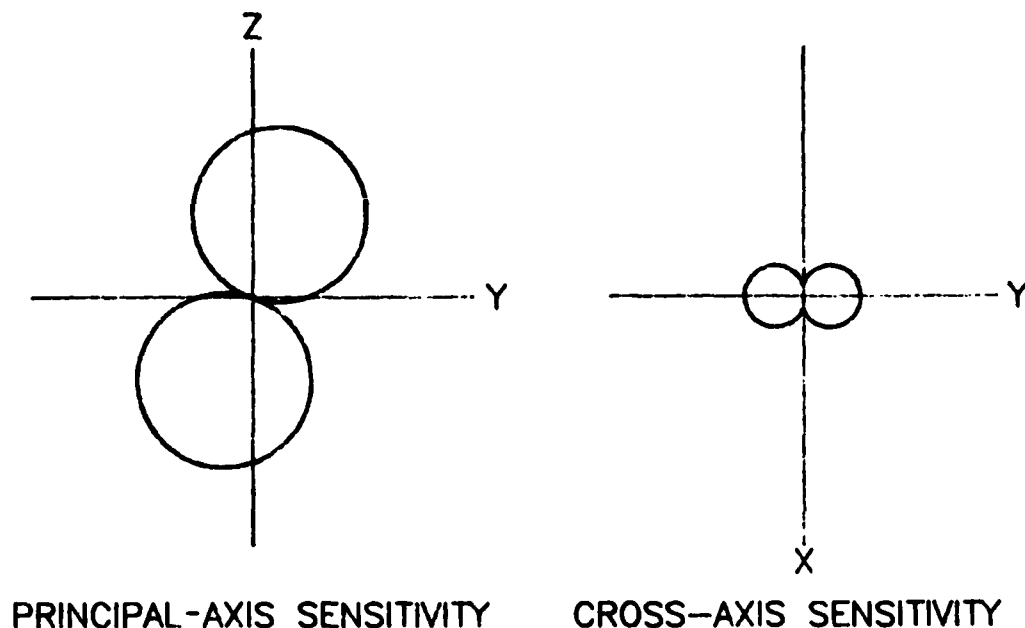
3. The frequency response of both the principal and cross axes is required for ballistic environments; it is reasonable to assume that the cross-axis environment is going to be the same order of magnitude as the principal-axis environment with the exception of on-board projectile

---

<sup>5</sup> J.N. Walbert, "Application of Digital Filters and Fourier Transform to the Analysis of Ballistic Data," BRL Technical Report ARBRL-TR-02347, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1981. (AD# A102890)

<sup>6</sup> P.L. Walter, "Deconvolution as a Technique to Improve Measurement System Data Integrity," Experimental Mechanics, Vol. 21, No. 8, August 1981.

<sup>7</sup> J.O. Pilcher, "Effects of Nonlinear Response of Ballistic Measurements," Ballistic Research Laboratory Aberdeen Proving Ground, MD, forthcoming.



**Figure 9. Orthogonal Sensitivity Properties**

measurements where the cross-axis environment can be several orders of magnitude greater than the principal-axis environment, depending on sensor orientation.

#### **B. General Response Requirements**

The accelerometer must survive and provide a sufficient range of measurement in the ballistic environment. Local mechanical filters and fixtures will have to be employed to ameliorate the strain wave effects. Wherever possible, these filters and fixtures should be included as part of the sensors in the calibration. However, accelerometers must have the following properties.

1. Linearity. Linearity should be within 1% absolute over the range of measurement.
2. Frequency Response. The frequency response should be within plus or minus 1% from .01 Hz to 10,000 Hz.
3. Amplitude Requirements. Amplitude ranges are  
     for guns - 2,000 G, and  
     for projectiles,  
         current - 20,000 G, and  
         future - 50,000 G.
4. Cross-Axis Sensitivity. Maximum cross-axis sensitivity should be less than 1%.

5. Matched Accelerometers. The difference between cross-axis sensitivities for a matched pair of accelerometers should be less than 0.1%.

6. Volume and Mass Properties. The volume and mass of the accelerometers must be as small as possible with respect to the structure on which they are mounted.

#### C. User Responsibility

The above requirements can be provided by a vendor, but must be verified by the user. The main problem is that the vendor cannot predict the mounting and environmental condition in which his sensor will be used. The user must either recalibrate the sensor in-house or collaborate with the vendor to obtain a suitable calibration under realistic conditions of use. This is probably the most difficult procedure to practice and the most ignored. The lack of realistic calibration conditions presents the largest source of measurement error, particularly in the ballistic environment.

### VII. SUMMARY

- The acceleration environment for real ballistic systems is beyond our ability to accurately predict due to strain wave effects.
- At this time, mechanical filtering appears to be the most viable solution to the strain wave interference problem.
- The complexity of acceleration fields requires that an array of matched pairs of accelerometers be used to determine principal vector components. Predictive model outputs must be tailored to the measurement, taking into account array geometry and vectorial sensitivity.
- Electronic and digital filtering techniques must be used with caution; at a minimum, system bandwidths must be opened up sufficiently to examine the overall measurement system performance during the initial phase of any given test series.
- Calibrations must be extended to encompass the spatial and frequency behavior of the sensor. In addition, calibrations must include the mounting and environmental conditions of the actual measurement.

#### REFERENCES

1. S.W. McCuskey, Introduction to Advanced Dynamics, Addison-Wesley Publishing Company, Reading, MA, pp 28-33, 1958.
2. J.O. Pilcher II, "Theoretical Consideration in Measuring Six-Degree-of-Freedom Motion of Gun Tubes by Accelerometers," ARBRL-TR-02474, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1983. (AD# A125474)
3. C.M. Harris and C.E. Crede, Shock and Vibration Handbook Vol. 2, McGraw-Hill Book Company Inc., New York, Chapter 30, p 53, 1961.
4. J.O. Pilcher, "Application of Mechanical Filters to Ballistic Measurements," Ballistic Research Laboratory, Aberdeen Proving Ground, MD, forthcoming.
5. J.N. Walbert, "Application of Digital Filters and Fourier Transform to the Analysis of Ballistic Data," BRL Technical Report ARBRL-TR-02347, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1981. (AD# A102890)
6. P.L. Walter, "Deconvolution as a Technique to Improve Measurement System Data Integrity," Experimental Mechanics, Vol. 21, No. 8, August 1981.
7. J.O. Pilcher, "Effects of Nonlinear Response of Ballistic Measurements," Ballistic Research Laboratory, Aberdeen Proving Ground, MD, forthcoming.

# DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
12	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22314	5	Commander USA AMCCOM, ARDC ATTN: SMCAR-LCU, E. Barrieres SMCAR-LCU, R. Davitt SMCAR-LCU-M, D. Robertson SMCAR-LCU-M, M. Weinstock SMCAR-LCA, C. Larson Dover, NJ 07801
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333	3	Commander USA AMCCOM, ARDC ATTN: SMCAR-LCA, B. Knutelski SMCAR-LCR-R, E.H. Moore III SMCAR-LCS-D, K. Rubin Dover, NJ 07801
1	Commander USA BMD Advanced Technology Center ATTN: BMDATC-M, P. Boyd P.O. Box 1500 Huntsville, AL 35804	7	Commander USA AMCCOM, ARDC ATTN: SMCAR-SCM SMCAR-SCS, B. Brodman SMCAR-SCS, T. Hung SMCAR-SCA, W. Gadomski SMCAR-SCA, E. Malatesta SMCAR-SCA-T, P. Benzkofer SMCAR-SCA-T, F. Dahdouh Dover, NJ 07801
1	Commander US Army Materiel Command ATTN: AMCLDC 5001 Eisenhower Avenue Alexandria, VA 22333	3	Commander USA AMCCOM, ARDC ATTN: SMCAR-LCR, W. Williver SMCAR-LCA, S. Bernstein SMCAR-LCN, G. Demitrack Dover, NJ 07801
5	Commander USA AMCCOM, ARDC ATTN: SMCAR-TDC SMCAR-LC SMCAR-SE SMCAR-SA SMCAR-AC Dover, NJ 07801	4	Commander USA AMCCOM, ARDC ATTN: SMCAR-LCA, S. Yim SMCAR-LCA, L. Rosendorf SMCAR-LCA, S.H. Chu SMCAR-LCW, R. Wrenn Dover, NJ 07801
1	Commander USA AMCCOM, ARDC ATTN: SMCAR-TSS Dover, NJ 07801	1	HQDA DAMA-ART-M Washington, DC 20310
1	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905	1	AFWL/SUL Kirtland AFB, NM 87117
1	Commander US Army Development & Employment Agency ATTN: MODE-TED-SAB Fort Lewis, WA 98433		

# DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
2	Director USA AMCCOM, ARDC Benet Weapons Laboratory ATTN: SMCAR-LCB-RA, T. Simkins SMCAR-D, J. Zweig Watervliet, NY 12189	1	Commander USA Communications Research and Development Command ATTN: AMSEL-ATDD Fort Monmouth, NJ 07703
1	Director USA AMCCOM, ARDC Benet Weapons Laboratory ATTN: SMCAR-LCB-TL Watervliet, NY 12189	1	Commander USA Electronics Research and Development Command Technical Support Activity ATTN: AMDSD-L Fort Monmouth, NJ 07703
1	Commander USA AMCCOM, ARDC ATTN: Product Assurance Dir. SMCAR-QAR-RIB(D), D. Imhof Dover, NJ 07801	3	Commander USA Harry Diamond Laboratories ATTN: DELHD-I-TR, H.D. Curchak DELHD-I-TR, H. Davis DELHD-S-QE-ES, B. Banner 2800 Powder Mill Road Adelphi, MD 20783
1	Commander USA AMCCOM, ARDC ATTN: SMCAR-TSE, L. Goldsmith Dover, NJ 07801	1	Commander USA Harry Diamond Laboratories ATTN: DELHD-TA-L 2800 Powder Mill Road Adelphi, MD 20783
1	Commander USA ARRCOM, ARDC ATTN: AMSMC-TSE-SW, R. Radkiewicz Rock Island, IL 61299	1	Commander USA Missile Command ATTN: AMSMI -R Redstone Arsenal, AL 35898
1	Commander USA ARRCOM, ARDC ATTN: AMSMC-LEP-L Rock Island, IL 61299	1	Commander USA Missile Command ATTN: AMSMI -YDL Redstone Arsenal, AL 35898
1	Commander USA Aviation Research and Development Command ATTN: AMSAV-E 4300 Goodfellow Blvd. St. Louis, MO 63120	1	Commander USA Tank Automotive Research and Development Command ATTN: AMSTA-TSL Warren, MI 48090
1	Director USA Air Mobility Research and Development Laboratory Ames Research Center Moffett Field, CA 94035		

# DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
2	Commander USA Jefferson Proving Ground ATTN: STEJP-TD-O, A. Tilley STEJP-TD-E, J. Toomey Madison, IN 47251	3	Project Manager Cannon Artillery Weapons Systems ATTN: AMCPM-CAWS Dover, NJ 07801
1	Director USA TRADOC Systems Analysis Activity ATTN: ATAA-SL WSMR, NM 88002	1	Product Manager for 30mm Ammo ATTN: AMCPM-AAH-30mm Dover, NJ 07801
2	Commander USA Yuma Proving Ground ATTN: STEYP-MTW, R. Torp G. Stullenbarger Yuma, AZ 85365	2	Product Manager M110E2 Weapon System, DARCOM ATTN: AMCPM-M110E2 Rock Island, IL 61299
2	Commander USA Research Office ATTN: E. Saibel P.O. Box 12211 Research Triangle Park NC 27709	2	Commander USA Materials and Mechanics Research Center ATTN: J. Mescall Tech. Library Watertown, MA 02172
3	Commander USA Research Office P.O. Box 12211 ATTN: Engineering Division Metallurgy & Materials Division Research Triangle Park NC 27709	2	Commander Naval Sea Systems Command (SEA-03513) ATTN: L. Pasiuk Washington, DC 20360
2	Project Manager Nuclear Munitions ATTN: AMCPM-NUC Dover, NJ 07801	1	Commander Naval Explosive Ordnance Disposal Facility ATTN: Lib Div Indian Head, MD 20640
2	Project Manager Tank Main Armament Systems ATTN: AMCPM-TMA Dover, NJ 07801	1	Superintendent Naval Postgraduate School ATTN: Dir of Lib Monterey, CA 93940
2	Project Manager ATTN: AMCPM-ADG, Sergeant York Dover, NJ 07801	1	Commander Naval Surface Weapons Center ATTN: G-13, W.D. Ralph Dahlgren, VA 22448



# DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
5	Commander Naval Surface Weapons Center ATTN: Code G-33, T.N. Tschirn Code N-43, J.J. Yagla L. Anderson G. Soo Hoo Code TX, W.G. Soper Dahlgren, VA 22448		Aberdeen Proving Ground Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen Cdr, USATECOM ATTN: AMSTE-TO-F Cdr, CRDC, AMCCUM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-SPS-IL Cdr, USACSTA ATTN: D. Dykstra J. Fasig S. Walton
2	Commander Naval Weapons Center ATTN: Code 3835, R. Sewell Code 3431, Tech Lib China Lake, CA 93555		
2	Commander US Naval Weapons Center ATTN: Code 608, R. Derr Code 4505, C. Thelen China Lake, CA 93555		
2	Commander Naval Ordnance Station ATTN: Code 5034, C. Irish, T.C. Smith Indian Head, MD 20640		
4	AFATL Gun and Rocket Division Gun Test Branch AD3246 TEST W/TETFG ATTN: W. Dittrich; DLJM D. Davis; DLDL Eglin AFB, FL 32542		
1	Southwest Research Institute ATTN: P. Cox 8500 Gulebra Road San Antonio, TX 78228		
1	AFELM, The Rand Corporation ATTN: Library-D 1700 Main Street Santa Monica, CA 90406		

# USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number \_\_\_\_\_ Date of Report \_\_\_\_\_
2. Date Report Received \_\_\_\_\_
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
4. How specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided or efficiencies achieved, etc? If so, please elaborate. \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
6. General Comments. What do you think sh. uld be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

CURRENT ADDRESS

\_\_\_\_\_  
Name  
\_\_\_\_\_  
Organization  
\_\_\_\_\_  
Address  
\_\_\_\_\_  
City, State, Zip

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

\_\_\_\_\_  
Name  
\_\_\_\_\_  
Organization  
\_\_\_\_\_  
Address  
\_\_\_\_\_  
City, State, Zip

(Remove this sheet along the perforation, fold as indicated, staple or tape closed, and mail.)

----- FOLD HERE -----

Director  
US Army Ballistic Research Laboratory  
ATTN: AMXBR-OD-ST  
Aberdeen Proving Ground, MD 21005-5066

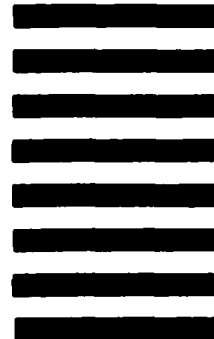


NO POSTAGE  
NECESSARY  
IF MAILED  
IN THE  
UNITED STATES

OFFICIAL BUSINESS  
PENALTY FOR PRIVATE USE, \$300

**BUSINESS REPLY MAIL**  
FIRST CLASS PERMIT NO 12062 WASHINGTON, DC  
POSTAGE WILL BE PAID BY DEPARTMENT OF THE ARMY

Director  
US Army Ballistic Research Laboratory  
ATTN: AMXBR-OD-ST  
Aberdeen Proving Ground, MD 21005-9989



----- FOLD HERE -----